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Influence of the proportion of materials on the rheology and mechanical strength of ultrahigh-performance concrete

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ABSTRACT

The present research investigates the influence of constituent material ratio on the fresh characteristics and compressive and flexural strengths of ultrahigh-performance concrete. In this regard, the influence of superplasticiser content of 1%, 1.3%, and 1.5%, microsilica substitution values of 20%, 25%, and 30%, and three water-to-binder ratios of 0.20, 0.22, and 0.24 on squeeze flow (SqF) characteristics and compressive and flexural strengths were evaluated. The findings revealed that increasing the superplasticiser dose enhanced compressive strength by up to 12% while increasing the water-to-binder ratio lowered it by up to 14%. Moreover, by increasing the amount of binder and/or decreasing the amount of sand, the concrete skeleton structure was broken down, which lowered the compressive strength.

1. Introduction

Ultrahigh-performance concrete is a type of concrete that is produced to attain high compressive strengths [1]. Ultrahigh-performance concretes outperform ordinary concrete in terms of engineering characteristics [2]. When multiple sorts of superplasticisers are applied, ultrahigh-performance concretes with an exceptionally low water-to-binder ratio can give appropriate rheological characteristics via optimum granular packing combination [3–6]. Autoclave curing can attain the strength of ultrahigh-performance concrete under ambient curing conditions that persist for 28-d in 24 h [2]. Autoclave and steam and curing techniques outperform ambient curing conditions, increasing the compressive strength of all samples by 25–63 % and 9–61 %, respectively [7]. Ultrahigh-performance concretes are often intended to have minimal porosity in their micro/macrostructure due to their high packing density [8–10].

ultrahigh-performance concretes have been shown to have a higher viscosity than ordinary concrete. The flowability of fresh ultrahigh-performance concrete may be determined using rheological and early-age characteristics. The behaviour of material throughout this period, nevertheless, has a considerable influence on the mechanical characteristics of ultrahigh-performance concrete [11–14]. The compact packing of raw components like cement, microsilica, fine aggregates, and superplasticisers has a direct impact on the behaviour of fresh ultrahigh-performance concrete. When the content of fine aggregates rises, yield or shear stresses, for instance, tend to rise [15–17].

The rate of change in cement-based pastes and mortars, on the other hand, varies. Choosing the right superplasticisers is crucial

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Table 1
Physical characteristics of cement-based materials.

Physical Characteristics	Specific area (cm^2/gm)	Mean grain size (μm)	Colour	Initial setting (min)	Final setting (min)	Density (g/cm^3)	Specific gravity
Microsilica	150000–300000	0.15	Light to Dark Grey	–	–	2.21	3.1
Cement	3250	22.5	Dark Grey	45	360	3.15	2.2

Table 2
Chemical compositions of cement-based materials.

Compositions (%)	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	Na_2O	K_2O	SO_3	LOI
Microsilica	0.7	1.12	85	0.8	1.46	0.8	1.056	–	< 6
Cement	63.61	5.04	20.25	4.56	3.16	0.08	0.51	2.1	3.13

Table 3
Aggregate grading.

Sieve size (mm)	Passing (%)	ASTM M778 [49] Requirements (%)
1.18	100	100
0.6	98	96–100
0.425	70	65–75
0.3	25	20–30
0.15	4	0–4

since flowability and rheology suffer if their composition with a cement-based matrix is not carefully selected [18–23]. Polycarboxylates based on methacrylate had substantial interaction with cement, but Polycarboxylates based on allyl ether had more compatibility and efficacy with microsilica, according to Schröfl, Gruber and Plank [24]. Furthermore, binary Polycarboxylates mixes had superior dispersion findings than unary mixes. Another research by Van Tuan, Ye, Van Breugel, Fraaij and Dai Bui [25] found that increasing the microsilica substitution content to 40 % boosted the superplasticisers doses dramatically to 2.38 %.

Dils, Boel and De Schutter [26] discovered that ultrahigh-performance concrete with an adequate combination of tricalcium aluminate's specific surface and alkalis value or sulfur trioxide had better rheological characteristics. The shifting carbon concentration of the microsilica inhibited production, reducing ultrahigh-performance concrete fluidity [27–33]. Moreover, some studies [34–38] suggest that the presence of micro or nano-silica declines accessible free water content inside interparticle gaps while increasing rheological indices.

Several rheometers have been employed by investigators to assess the yield stress, plastic viscosity, and shear stress of cement-based composites. SqF testing is a novel approach that has lately been used [30,31,39,40]. The SqF test has declined certain frequent rheological issues like slippage, loading difficulties, and expanding materials or fibrous fluid. Furthermore, its use to evaluating the rheology and tribological behaviour of quasi-plastic fluids or high viscosity mixes is growing [41–45]. The early investigations on the SqF technique can be used to evaluate studies on the rheological behaviour of new cement-based mortar or paste as determined by SqF [28,46].

The current work outlines the use of a SqF test to assess the rheological behaviour of ultrahigh-performance concrete. In this respect, the impacts of several factors like superplasticisers of 1 %, 1.30 %, 1.50 %, microsilica of 20 %, 25 %, 30 %, and three water-to-binder ratios of 0.20, 0.22, 0.24 on fresh characteristics and mechanical strength of ultrahigh-performance concrete were studied.

2. Research significance

Due to the advantages and challenges specific to the ultrahigh-performance concretes, additional studies are warranted. This paper aims to improve the understanding of ultrahigh-performance concretes by investigating the influence of constituent material ratio on the compressive and flexural strengths of ultrahigh-performance concrete.

3. Experimental program

3.1. Materials

Portland cement (PC) I 42.5 was utilized in this study in line with ASTM C 150 [47]. In accordance with ASTM C 1240 [48], microsilica was employed as a pozzolanic additive material as a partial substitute for cement. Tables 1 and 2 list the characteristics of cement-based materials. The river sand provided by River Sands Pty Ltd was in conformity with ASTM C 778 [49], and its grain size is shown in Table 3. Table 4 shows the factors of a polycarboxylate-based superplasticiser applied based on ASTM C 494 [50].

Table 4
Characteristics of the used superplasticiser.

Items	Characteristics
Appearance	Light brownish liquid
Chemical composition	Modified poly carboxylates-based polymer
Density (20 °C)	1.1 g/cm^3
Ionic nature	Anionic
Chloride (ppm)	Max 500
pH	3–7
Dosage	1.0–2.0% by weight of cement

Table 5
Mixing proportion of ultrahigh-performance concrete (wt of cement).

Group	Stage	Mix No.	Cement	Sand	Microsilica	Superplasticiser (×100)	Water/binder
I	A	M1	1	2.2	0.18	1.53	0.22
		M2		2.3	0.26	1.55	0.22
		M3		2.40	0.34	1.65	0.22
	B	M4	1	2.25	0.18	1.56	0.20
		M5		2.15	0.18	1.56	0.24
		M6		2.20	0.18	1.70	0.22
		M7		2.21	0.18	1.20	0.22
II	A	M8	1	1.75	0.18	1.55	0.22
		M9		1.85	0.26	1.56	0.22
		M10		1.85	0.34	1.65	0.22
	B	M11	1	1.90	0.26	1.55	0.20
		M12		1.80	0.26	1.55	0.24
		M13		1.85	0.26	1.80	0.22
		M14		1.86	0.26	1.35	0.22
III	A	M15	1	1.42	0.18	1.55	0.22
		M16		1.57	0.26	1.55	0.22
		M17		1.59	0.34	1.65	0.22
	B	M18	1	1.49	0.18	1.45	0.20
		M19		1.38	0.18	1.45	0.24
		M20		1.42	0.18	1.70	0.22
		M21		1.44	0.18	1.22	0.22

3.2. Mix design proportions

The fabrication and molding of the combination were conducted in line with ASTM C 109 [51] with certain changes [29]. At first, the solid raw ingredients, which included cement, sand, and microsilica, were gently mixed till the microsilica particles were evenly dispersed among the other solid elements and a considerable decline in the bulk volume of the blend was seen. This volume change is controlled to some extent in the original mix design by using low water and low sand contents [28,30]. The water-superplasticiser combination was then carefully added to the dry mix, and the blending technique was repeated for 90 s at a low speed. After the paste was formed, the mixing speed was raised and maintained for 130 s [29]. Finally, the mixes were fully made and consistent. The combination was molded into molds for mechanical testing after fresh characteristics were evaluated. The molds were covered with plastic sheets and cured for 24 h at room temperature and 75 % relative humidity. Following that, the test specimens were put in a water tank for 7- and 28-d, respectively, till the day of testing. In this study, microsilica substitution values of 20 %, 25 %, and 30 % by weight of cement, superplasticisers 1 %, 1.3 %, and 1.5 %, three binder contents of 850, 950, and 1050 kg/m^3, and three water-to-binder ratios of 0.20, 0.22, and 0.24 were used to assess ultrahigh-performance concrete characteristics. In two steps, ultrahigh-performance concrete mixes were labeled and evaluated. Stage A goal was to determine the optimal quantity of microsilica using a 28-d compressive strength test. Stage B looked at how water-to-binder and superplasticisers affected mechanical characteristics. Table 5 shows the proportions of ultrahigh-performance concrete in the blends.

3.3. Testing procedure

The SqF test was carried out using two circular plates with diameters of 90 mm and lengths of 20 mm. The starting distance between plates after applying the paste was 30 mm and loading rates of 1 and 10 mm/s were used [29]. The displacement percent was calculated as the ratio of the sample's momentary height to its original height.

Compressive strength tests were done on 27 cubic specimens with dimensions of 50 × 50 × 50 mm at the ages of 7- and 28-d in line with ASTM C 109 [51]. Flexural strength tests were also done on 9 prismatic specimens with dimensions 40 × 40 × 160 mm in accordance with [52].

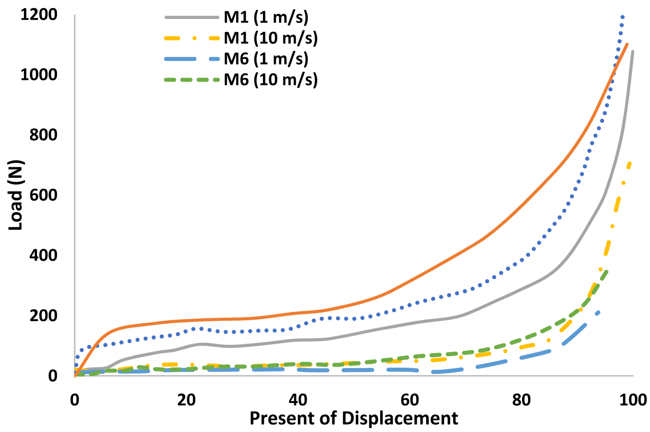

Fig. 1. I-group pastes load–displacement curves under SqF test with different superplasticisers dosages and displacement rates.

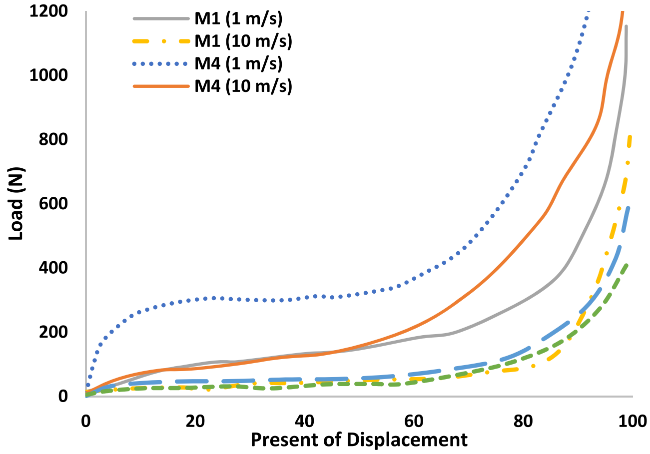

Fig. 2. I-group pastes load–displacement curves under SqF test with different water-to-binder ratio and displacement rates.

4. Findings and discussion

4.1. Rheological characteristics

The influence of superplasticisers doses and displacement rates on the findings of the I-group paste SqF test is shown in Fig. 1. The profiles of the shifted down curves reveal that raising the superplasticisers doses declines the necessary SqF load. When 1.5% superplasticisers paste is used, it causes greater displacement than pastes with lower doses [29,32]. Furthermore, lower superplasticisers doses produce a substantially less plastic deformation step than higher dosages. It also declines flowability and condensation resistance to some amount. Decreasing the paste flow declines the propensity of strain-hardening behaviour, which may be explained by the quick transfer from the beginning position [28,31]. High SqF rates improve paste loading and decline relative displacement, which is especially noticeable for paste comprising 1% superplasticisers.

The influence of water-to-binder ratio and displacement rates on the findings of the I-group paste SqF test is shown in Fig. 2. The curve profiles are positioned higher for the low water-to-binder ratio. Furthermore, as compared to other curves, they exhibit a lower stage. As a result, the necessary load for paste SqF increases for water-to-binder ratios of 0.22. Furthermore, since it is dry, its plastic deformation reduces, accelerating the strain-hardening step. The presence of strain-hardening behaviour shows that there is a significant friction between the paste's components owing to slip and lubricant inadequacy [30,46]. Furthermore, by raising the SqF rate, the curves are pushed to a higher location, leading in bigger displacements at lower values. This behaviour is thought to be the consequence of the paste's ability to cause dilatancy. This implies that the distance between solid particles varies during elastic deformation, and during the plastic stage, voids or air gaps occur in the matrix, leading in dilatancy. Increasing the water-to-binder ratio, on the other hand, may lessen the propensity of strain-hardening behaviour [28,31]. If the water-to-binder ratio is increased to 0.24, the displacement value for SqF speeds of 1 and 10 mm/s is 55% and 45%, respectively.

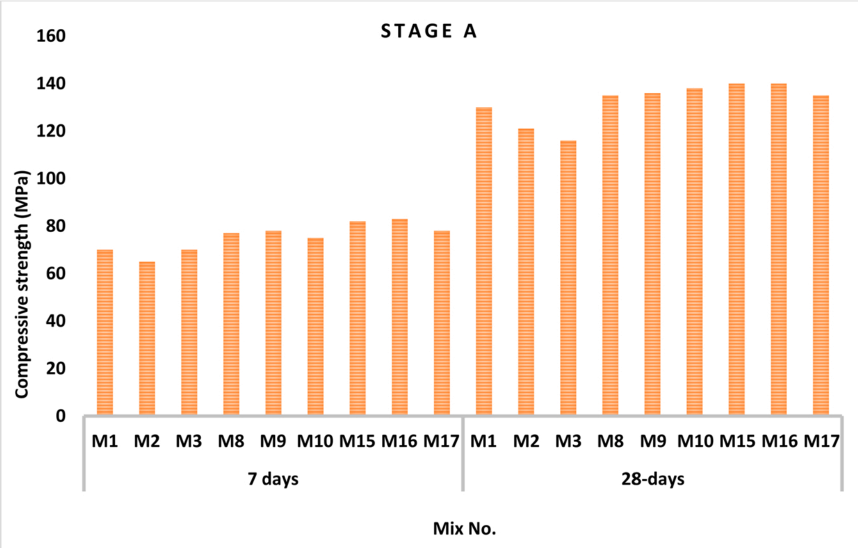

Fig. 3. Compressive strength of stage A ultrahigh-performance concrete mixes.

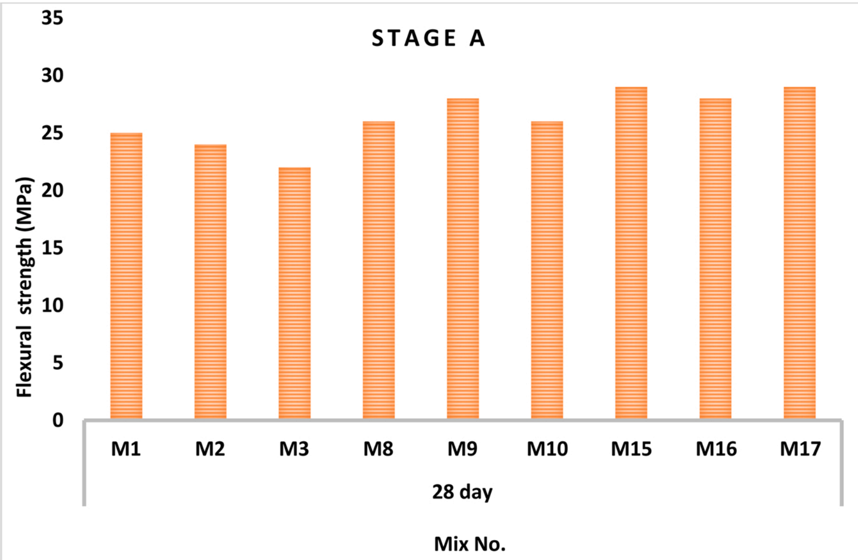

Fig. 4. Flexural strength of stage A ultrahigh-performance concrete mixes.

4.2. Mechanical strength

Figs. 3 and 4 show the compressive and flexural strength data for stage A. The maximum compressive strength among the group I mixes at 7- and 28-d belongs to M1 and M1 mixes, respectively. The findings show that integrating 20 % microsilica results in the greatest strength. It may be stated that when microsilica substitution increases, compressive strength reduces at both ages [53–56]. The problem seems to be integrating more than the recommended quantity of microsilica. This behaviour is also thought to be caused by a large volume of cement-based paste in the matrix and a lack of time for additional hydration processes [46,57–60]. At 7 or 28-d, no significant variations in compressive strength are detected in II or III group combinations when the quantity of microsilica is changed. The M9 and M15 mixes had the maximum compressive strength, with increases of 92 % and 85 %, respectively, compared to the age of 7-d. Reducing the content of sand declines the quality of the concrete skeleton structure while increasing the proportion of cement-based materials increases the likelihood of issues like shrinkage micro cracks. Furthermore, by reducing sand volume, the quantity of water around aggregate particles declines, leading to an increase in free water in the cement-based matrix [39,61–67].

The flexural strength of ultrahigh-performance concrete diminishes as the microsilica concentration increases. When the quantity of microsilica in the I-group combinations reaches 30 %, the flexural strength declines by around 15%. For III group mixes, the

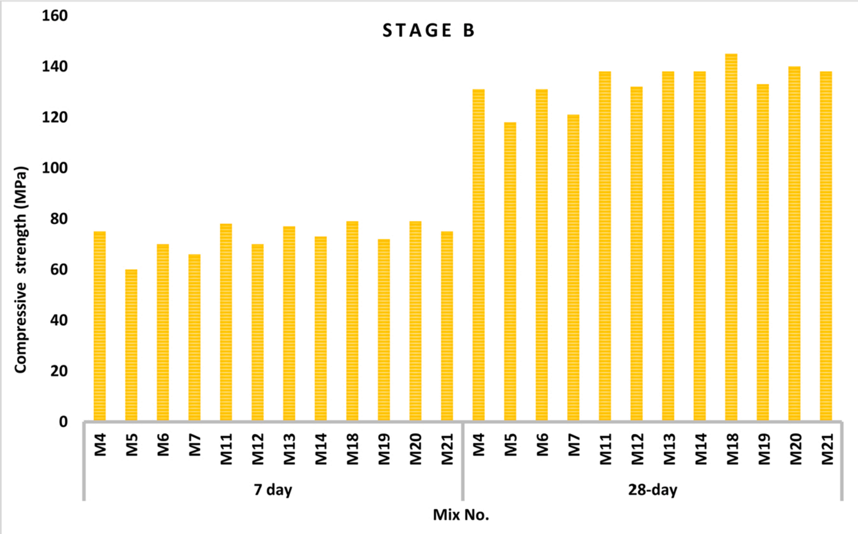

Fig. 5. Compressive strength of ultrahigh-performance concrete mix in stage B.

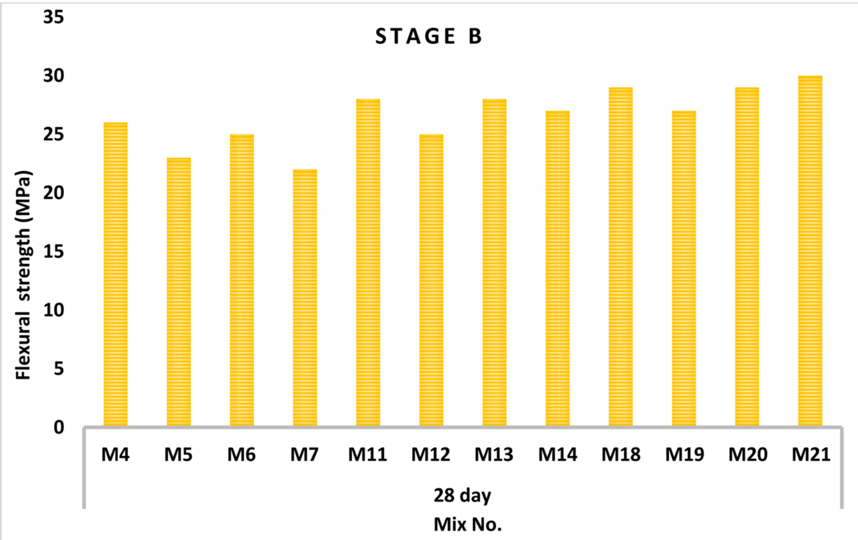

Fig. 6. Flexural strength of ultrahigh-performance concrete mix in stage B.

reduction is 6 %. Figs. 5 and 6 show the findings of compressive and flexural strengths during stage B. Based on the compressive strength result, M1, M12, and M17 specimens were presented as ideal mix designs, with 20 %, 25 %, and 25 % microsilica substitution, respectively.

The findings of the I-group mixes revealed that increasing the water-to-binder ratio from 0.20 to 0.24 declined compressive strength by up to 14 %. This behaviour may be caused by the reduction of free water and pores, as well as the reduction of tensions owing to shrinking [40,68–72]. When M7 and M6 mixes were compared, a high superplasticisers dose enhanced compressive strength by up to 12 %. The maximum compressive strength was obtained in group II and III combinations with a water-to-binder ratio of 0.20.

Fig. 7 depicts the influence of various superplasticisers doses on compressive strength at a fixed water-to-binder ratio of 0.2. The findings show that when the superplasticisers doses rose, the compressive strength increased [73–75].

The influence of water-to-binder ratio and superplasticisers doses on the compressive strength of ultrahigh-performance concrete after 28-d is shown in Fig. 8. When the superplasticisers dose is fixed, raising the water-to-binder ratio declines the compressive strength of ultrahigh-performance concrete [76–78]. The compressive strength decline rate in the group I combination is more noticeable, reducing strength by around 16 %. The mixes of group III, on the other hand, have the maximum compressive strength in the different water-to-binder ratios.

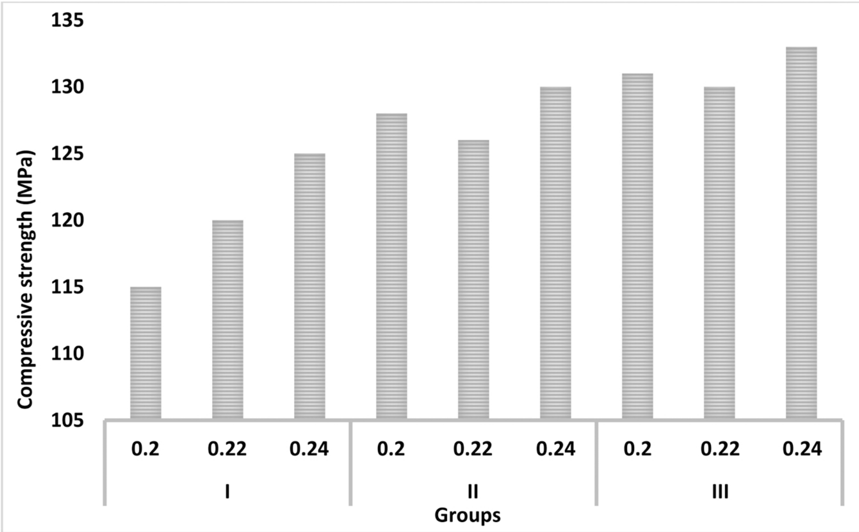

Fig. 7. The influence of superplasticisers doses on ultrahigh-performance concrete compressive strengths after 28-d.

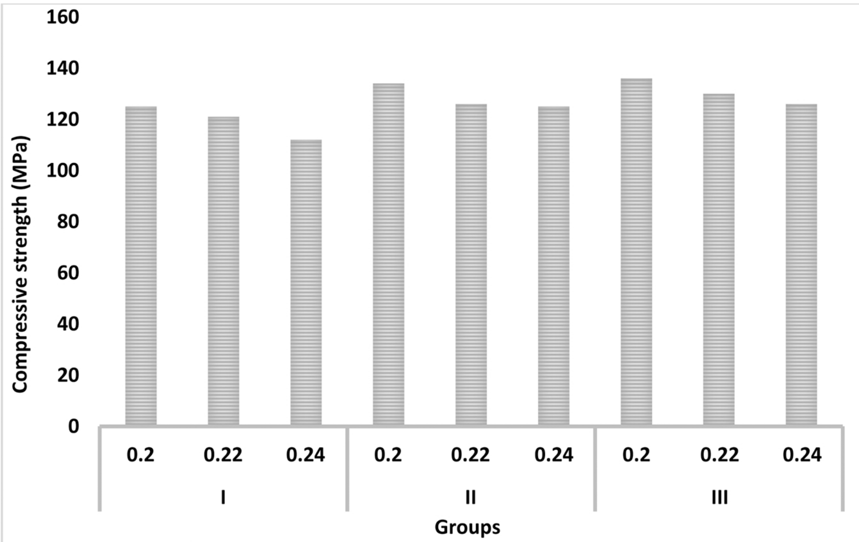

Fig. 8. The influence of water-to-binder on ultrahigh-performance concrete compressive strengths after 28-d.

5. Conclusions

Based on the findings, the following key conclusions can be drawn:

1. The raising of the superplasticiser doses decreases the necessary SqF load. Furthermore, lower superplasticiser doses produce a substantially lower plastic deformation step than higher dosages. Moreover, high SqF rates improve paste loading and decline relative displacement.
2. The result indicated that the curve profiles are positioned higher for the low water-to-binder ratio. Furthermore, since it is dry, its plastic deformation is reduced, accelerating the strain-hardening step.
3. Microsilica substitution ratios of 20 %, 25 %, and 30 % were found to have the most influence on the I-, III-, and II-groups, respectively.
4. By increasing the amount of binder and/or decreasing the amount of sand, the concrete skeleton structure was broken down, which lowered the compressive strength.
5. The findings revealed that increasing the superplasticiser dose enhanced compressive strength by up to 12 % while increasing the water-to-binder ratio lowered it by up to 14 %.

Future studies

In future research, it will be necessary to investigate the effects of other ratios different from those in this study, in addition to the ratios of other constituent materials, on the performance of mechanical ultrahigh-performance concrete in full depth.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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